AD623870

AFCRL-65-674
SEPTEMBER 1965
ENVIRONMENTAL RESEARCH PAPERS, NO. 136

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES

L. G. HANSCOM FIELD, BEDFORD, MASSACHUSETTS

Spectral Reflectance and Albedo Measurements of the Earth from High Altitudes

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Code 1

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ARPA Order No. 363

OFFICE OF AEROSPACE RESEARCH
United States Air Force

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OPTICAL PHYSICS LABORATORY PROJECT 8662

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Spectral Reflectance and Albedo Measurements of the Earth from High Altitudes

F[illegible]D*
L. C. BLOCK

* A member of the staff of Utah State University. He assisted in the research covered by this report working under Contract AF 19(628)3241.

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Abstract

Spectral radiance measurements over the wavelength range of 0.24 to 0.28 microns were carried out using Ebert-type scanning spectrometers mounted on the aft section of an X-15 aircraft operating up to 270,000 ft altitude. With the assumption of Rayleigh scattering in the atmosphere and allowing for ozone absorption, the reflectance and albedo are estimated and compared with the measured values. The elevations and azimuths of the sun and of the spectrometer during the flight were tabulated and used to compute the scattering and diffuse reflection angles. Apparent reflection of radiation from the ground is estimated, using a Lambert radiator model. Since the spectrometer at times pointed away from the earth, it should be possible to estimate the separate contribution of the ground to the reflectance and total albedo.

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Spectral Reflectance and Albedo Measurements of the Earth from High Altitudes *

1. INTRODUCTION

The Optics and Radiometry Branch of the Air Force Cambridge Research Laboratories has been actively engaged in making measurements from on-board missiles and satellites.† As a part of this over-all effort, a program has been established utilizing the X-15 aircraft as a space platform. A series of flights has been planned and carried out. The purpose of the measurements is to investigate high altitude plume radiation characteristics and to make background-radiation, scattering and albedo measurements. The advantage of using the X-15 vehicle is twofold: (1) the instrumentation is recoverable, and reusable for additional measurements and (2) precise altitude, viewing angles, aspect angles, and scattering angles can be determined. Altitude information is recorded on board the vehicle and is also telemetered to the ground station.

(Received for publication 18 May 1965)

*This paper is a revised version of one presented at the October 1963 Meeting of the Optical Society of America at Chicago, Illinois.

†Supported in part by the Advanced Research Projects Agency.

2. INSTRUMENTATION

The instruments used are passive optical sensors. Bracketry has been incorporated into the upper tail fin section of the X-15 to accommodate the instrumentation. The instrument itself can be changed from flight to flight as long as it maintains compatibility with the bracketry, cabling, telemetry and size limitations. Figure 1 shows the location of the instrument with respect to the X-15 aircraft.

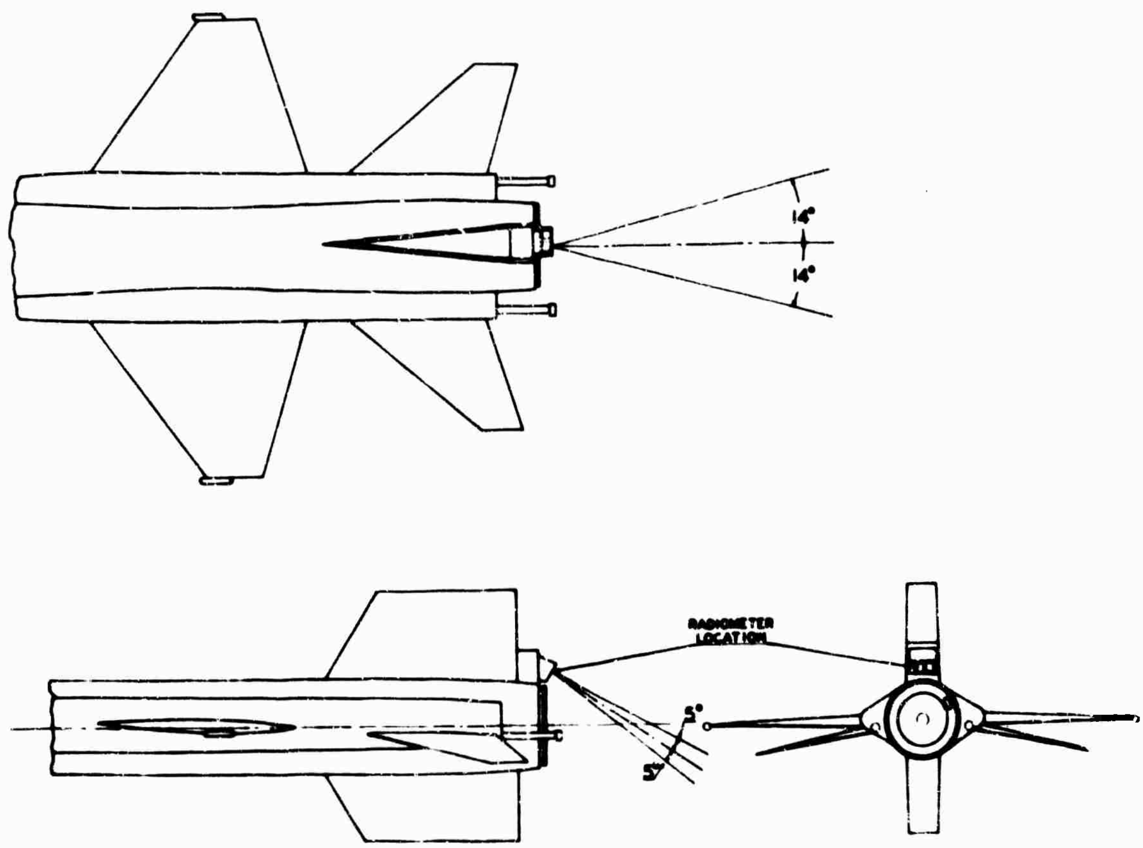

Figure 1. Radiometer Mounting on X-15 Body

On the first set of flights, the instrument used was a duel channel Ebert-type rocking grating spectrometer built by Block Engineering Company of Cambridge, Massachusetts. The spectral regions, the field of view, the dynamic range, and the gain setting can be varied from flight to flight. Instrumentation details have been presented by Block, Band and Dana (1963).

3. EXPERIMENTAL RESULTS

The radiometric data shown in the accompanying figures were obtained while the aircraft was on a constant heading (191° 48') and performed no maneuvers other than climbing and diving. A typical ground path and altitude profile are shown in Figures 2 and 3. Measurements taken prior to engine cutoff (80 sec after launch) were omitted as well as those taken after large changes of heading, and after the subsequent more involved maneuvering of the vehicle. This eliminates: (a) the engine exhaust radiation and (b) the radiometer pointing errors caused by the rapidly changing altitude of the vehicle during banking and turning. The portion of the flight reflected in the present data lasted from 80 to 280 sec after launch, a total of 200 seconds. During this time interval, the sun's altitude changed from 47° 41' to 48° 30' and its azimuth from 110° 43' to 109° 03' for a typical run (one λ - value) as seen by an observer located at the radiometer. These changes amount to 1.7% and 1.5%, respectively. The altitude and azimuth of the radiometer axis as well as of the sun were computed every 2 sec of flight time using the (time-varying) angle of attack* and the fixed angle between the plane's longitudinal axis and the optical axis of the radiometer. This latter angle is 30°; that is, the radiometer looks rearward 30° vertically below the plane's axis. The angular values of radiometer altitude and azimuth as well as those of the sun (as seen by an observer on the ground at point G in Figure 5) were then transformed to direction cosines of the lines Sun-Ground Point and Radiometer-Ground Point, respectively by the relations

$$l = \frac{X}{R} = \sin \zeta \cos \alpha$$

$$m = \frac{Y}{R} = \sin \zeta \sin \alpha$$

$$n = \frac{Z}{R} = \cos \zeta, \qquad (1)$$

where l, m, n are the direction cosines of a radius vector R having spherical polar coordinate components R, α, ζ (see Figures 4 and 5). The scattering geometry is illustrated in Figure 5 in which ψ is the usual scattering angle. The scattering volume element of the atmosphere, ΔV, can be assumed to lie anywhere along the line radiometer-ground point G. The justification for this is that due to the re-remoteness of the sun the angle θ changes only slightly as ΔV is moved from the

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* This is defined as the acute angle between the plane's longitudinal axis and the tangent to the plane's trajectory at that instant.

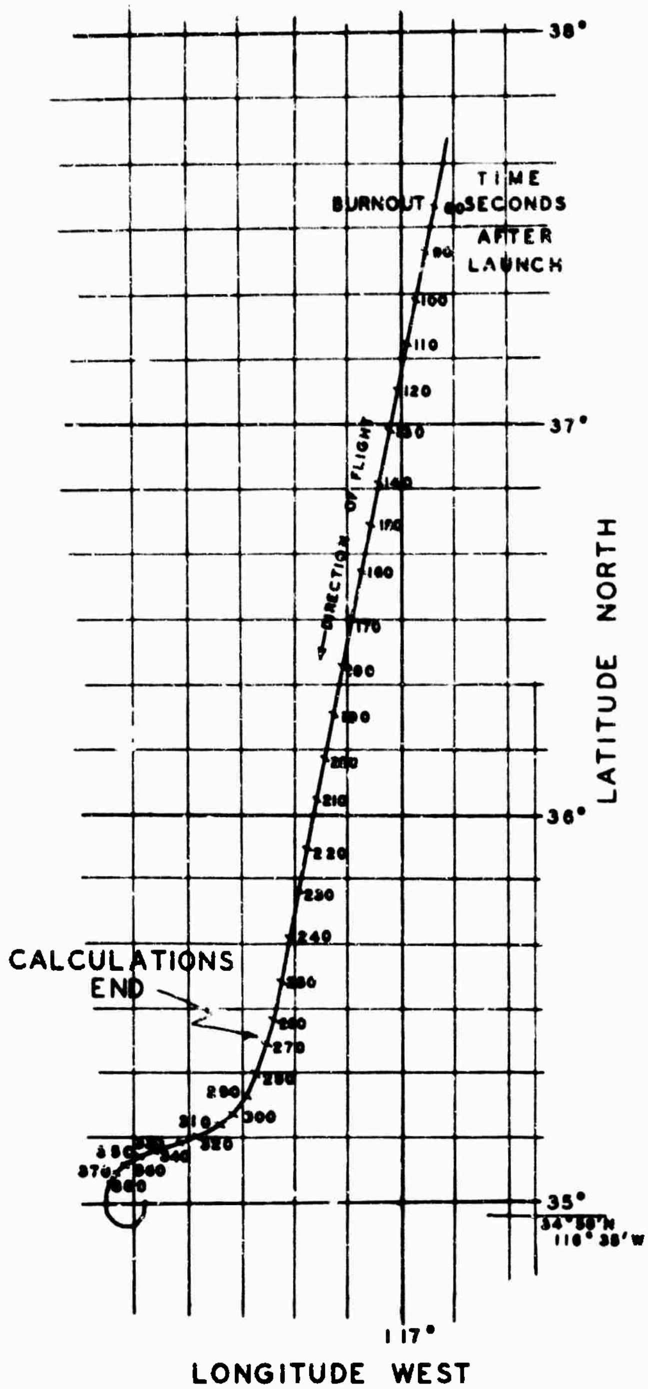

Figure 2. Ground Path of X-15

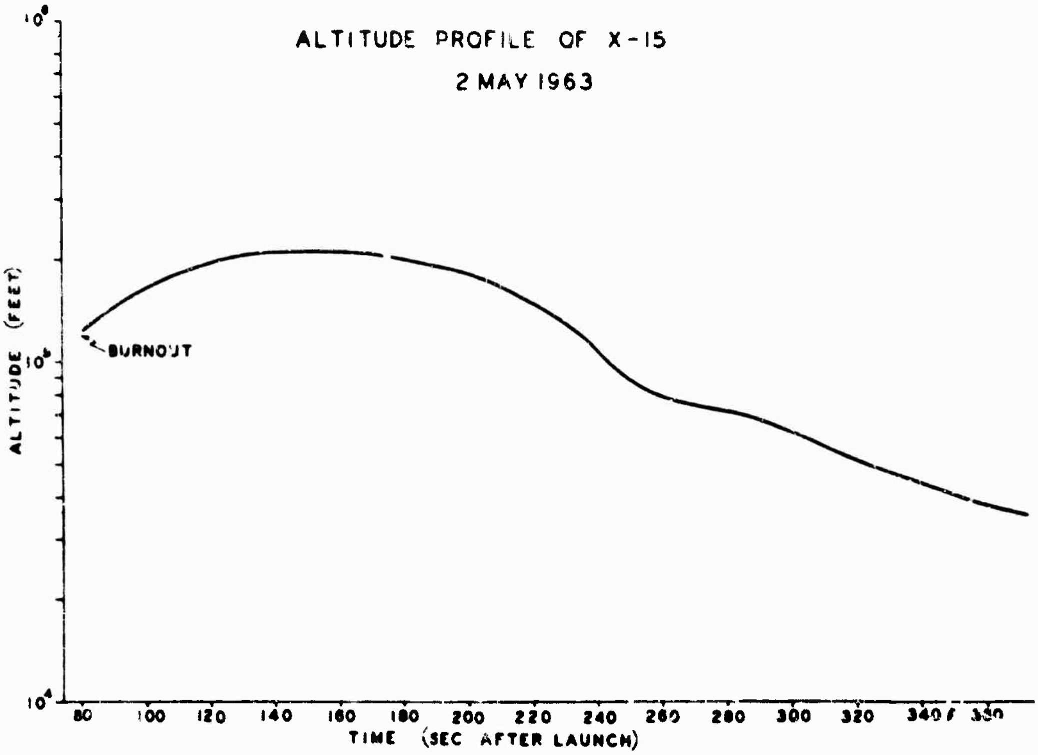

Figure 3. Altitude Profile of X-15

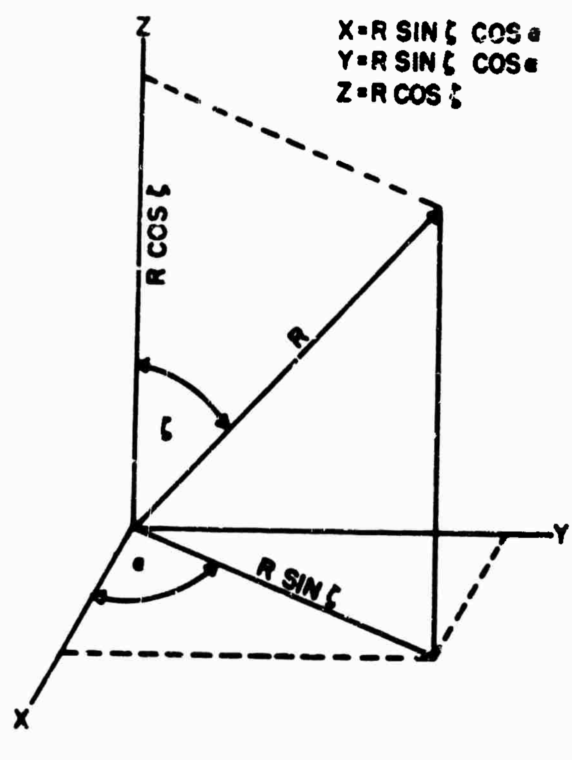

Figure 4. Spherical Polar Coordinate System

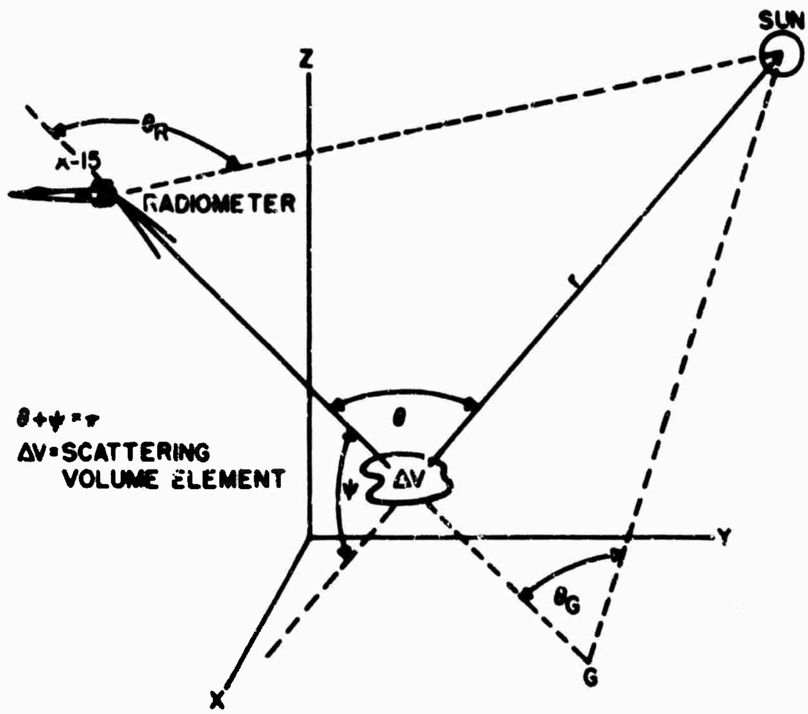

Figure 5. Geometry of Reflectance Measurements

radiometer entrance to the point G.* The latter is defined as the intersection of the extended radiometer axis with the earth's surface, considered plane for this purpose. The locus of G is plotted† during a typical flight in Figure 6. The supplement θ

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* A numerical check shows that for a 500 mile path from radiometer to ground the angle θ changes only by about 5×10^{-6} radian, when the ground point G is taken as the position from which the sun's altitude and azimuth are determined, instead of from the plane's position. Atmospheric refraction introduces an error of about one minute of arc in θ. At present calculations are being made of the exact error due to neglect of the earth's curvature. Preliminary checks indicate an upper limit of 0.6° for this (see Section 4).

† At the beginning of a typical data taking period the radiometer axis intersected the ground at 116° 54' longitude West, 37° 33' latitude North while the X-15 aircraft was climbing at 120,000 ft altitude. At a time 164 sec later the radiometer was pointing at a point on the ground located at 117° 21' longitude West, 35° 39' latitude North while the X-15 was diving from an altitude of 196,600 feet. At an intermediate point the plane was flying almost exactly level at 208,400 ft and the radiometer pointed at the ground at 117° 08' longitude West, 36° 36' latitude North. These terrain points lie in the Death Valley area of California and Southern Nevada, which is largely desert. Van de Hulst (1949) gives a (total) albedo of about 25% for deserts.

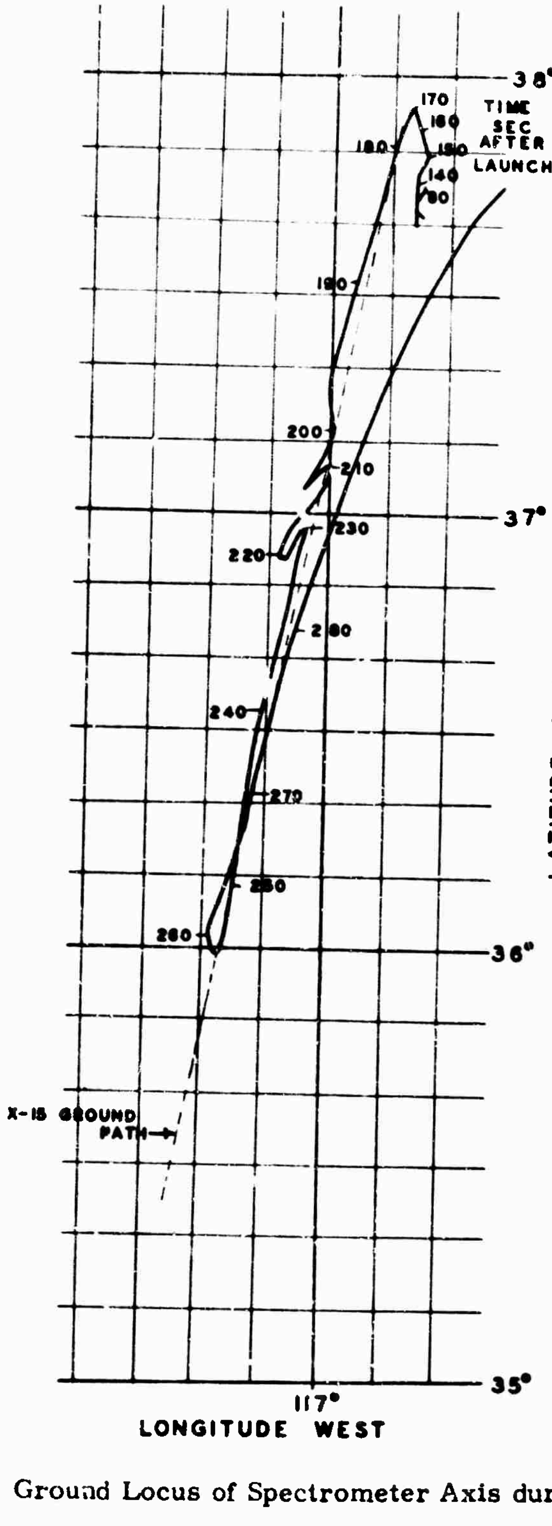

Figure 6. Ground Locus of Spectrometer Axis during Flight

of the conventional scattering angle ψ is given, using elementary analytic geometry, by the relation

$$\cos\theta = l_1 l_2 + m_1 m_2 + n_1 n_2, \tag{2}$$

where the subscripts refer to the lines "radiometer-scattering volume" and "sun-scattering volume", respectively. In terms of polar coordinate angles this becomes

$$\cos\theta = \sin\zeta_1 \sin\zeta_2 \cos(\alpha_1 - \alpha_2) + \cos\zeta_1 \cos\zeta_2. \tag{3}$$

In Figures 7 and 8 are shown the measured spectral radiance of the atmosphere and ground as a function of time and of the scattering angle ψ. The fractional contribution of ground-reflected solar radiation to the total measured radiance is claimed to be about 8% by Van de Hulst (1949) for λ = 5400 A skylight and a normal optical thickness τ = 0.1 for the atmosphere. In general the value of the spectral reflectance of the ground is largely unknown, however, and varies considerably with the nature of the ground.* A Lambert law reflecting ground was assumed, its spectral reflectance being called A.†

The radiometer spectral irradiance (watts/m^2/μ) was measured as a function of aircraft position and altitude. By postulating the applicable scattering and attenuation laws over the spectral region used, an attempt was made to determine the apparent ground reflectance and the normal optical thickness of the atmosphere below the radiometer, assuming a vacuum above. In the initial set of measurements,

*At the beginning of a typical data taking period the radiometer axis intersected the ground at 116° 54' longitude West, 37° 33' latitude North while the X-15 aircraft was climbing at 120,000 ft altitude. At a time 164 sec later the radiometer was pointing at a point on the ground located at 117° 21' longitude West, 35° 39' latitude North while the X-15 was diving from an altitude of 196,600 feet. At an intermediate point the plane was flying almost exactly level at 208,400 ft and the radiometer pointed at the ground at 117° 08' longitude West, 36° 36' latitude North. These terrain points lie in the Death Valley area of California and Southern Nevada, which is largely desert. Van de Hulst (1949) gives a (total) albedo of about 25% for deserts.

†Due to the well-known high absorption by ozone in the 2000-3000 A region the following data on A and τ must be considered inconclusive.

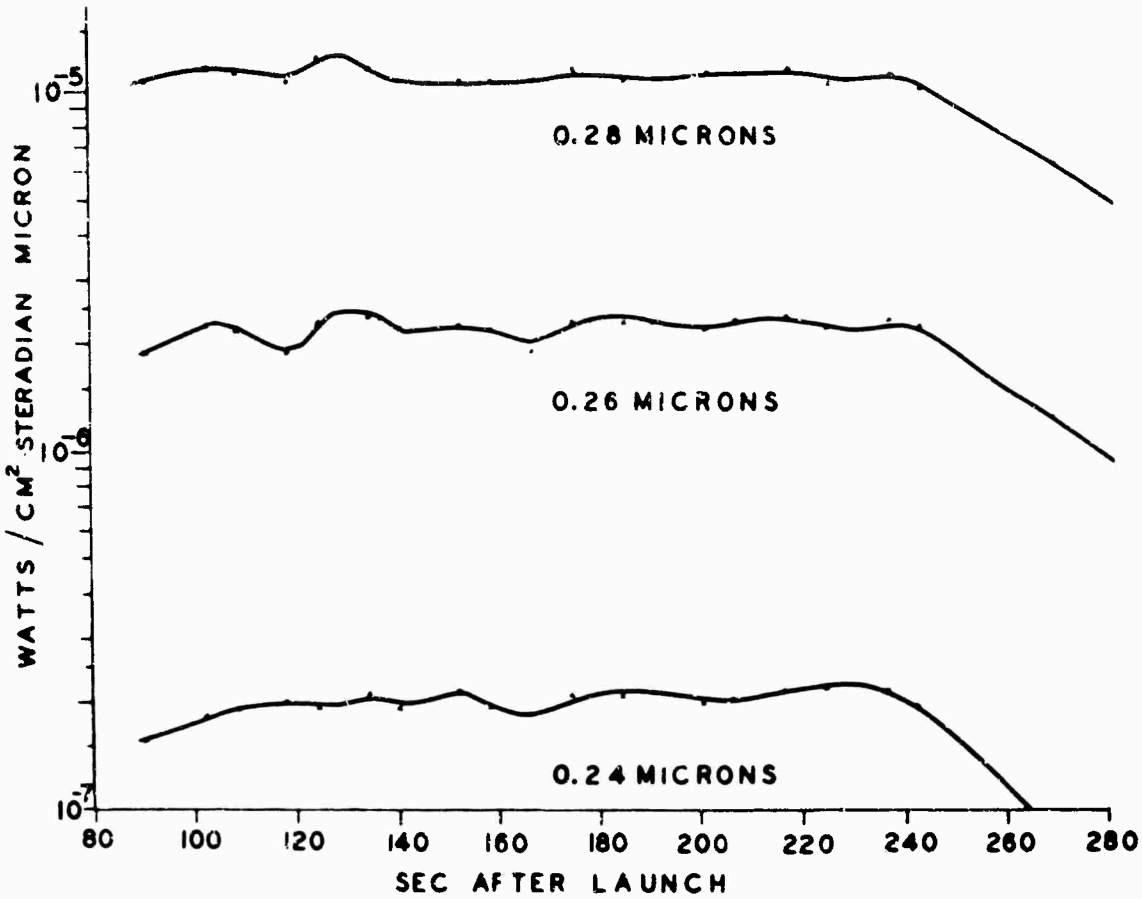

Figure 7. Spectral Radiance as a Function of Time

the wavelength range covered was 2400 to 2800 A. In this spectral range there is strong ozone absorption, and Rayleigh scattering is strongly effective. We therefore invoked Rayleigh scattering, ozone absorption (see approximation below), plus the Lambert Law ground reflection contribution which is probably relatively insensitive to wavelength. Curvature of earth and atmosphere, as well as atmospheric refraction were neglected. Only primary scattering was assumed to be present.

The scattered radiant intensity from ΔV is proportional to the solar irradiance at ΔV. If Rayleigh scattering holds and the normal optical thickness* of the atmosphere (from the ground to infinity) is taken as

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* The coordinate z measures vertical height above the ground.

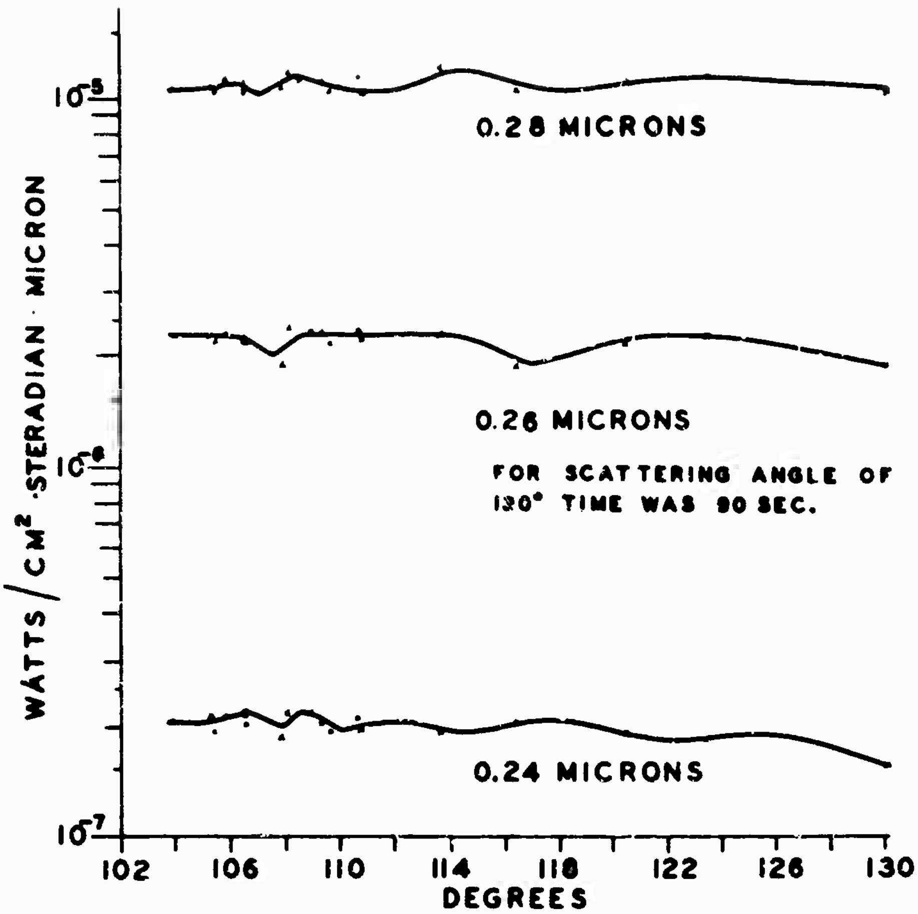

Figure 8. Spectral Radiance as a Function of Scattering Angle

$$\tau = \int_0^\infty \beta \, dz, \tag{4}$$

β being the extinction coefficient, then the scattered spectral radiance N seen by the radiometer from the top of the atmosphere is, according to Eq. 2. 23 in Coulson (1959),

$$N_\lambda^s = \frac{1}{4} F_\lambda \, P(\psi) \frac{\sec \zeta_1}{\sec \zeta_1 + \sec \zeta_2} \left[1 - e^{-\tau(\sec \zeta_1 + \sec \zeta_2)} \right] \tag{5}$$

where ψ is the Rayleigh scattering angle and $P(\psi) = 3/4\,(1+\cos^2\psi)$ the normalized Rayleigh scattering function. ζ_1 and ζ_2 are the zenith angles of the radiometer and the sun, respectively. F_λ is $\frac{1}{\pi}$ times the spectral irradiance (watts/ $cm^2\mu$) of the sun as measured incident on top of the atmosphere.

The contribution from ground-reflected solar radiation must next be estimated. This is given by Coulson (Eq. 2.28) as

$$N_\lambda^r = \frac{1}{2} A F_\lambda \cos\zeta_2 \, e^{-\tau(\sec\zeta_1 + \sec\zeta_2)} \tag{6}$$

where A is the fraction of the incident solar flux reflected isotropically by the ground. (The skylight, that is, the ground illumination contributed by scattered rather than directly incident sunlight is neglected here.) Adding these two contributions we get for the total spectral radiance seen by the radiometer at the top of the atmosphere (without ozone absorption)

$$N_\lambda = N_\lambda^S + N_\lambda^r =$$

$$\frac{1}{2} F_\lambda \left\{ \frac{1}{2} P(\psi) \frac{\sec\lambda_1}{\sec\lambda_1 + \sec\lambda_2} \left[1 - e^{-\tau(\lambda)(\sec\lambda_1 + \sec\lambda_2)} \right] \right.$$

$$\left. + \; A \cos\zeta_2 \, e^{-\tau(\lambda)(\sec\zeta_1 + \sec\zeta_2)} \right\},$$

$$0 < A < 1. \tag{7}$$

The normal optical thickness of the atmosphere $\tau(\lambda) = \int_0^\infty \beta(\lambda)\, dz$ is wavelength dependent through the extinction coefficient $\beta(\lambda)$.

By taking ratios of spectral radiance values at two different positions x and y of the radiometer and at the same wavelength we eliminate F_λ and get from Eq. (7)

$$R_{xy} = \frac{N_\lambda(x)}{N_\lambda(y)} = \frac{e^{-\tau(\lambda)(\sec\zeta_{1x} + \sec\zeta_{2x})} \left[A\cos\zeta_{1x} - G(x) \right] + G(x)}{e^{-\tau(\lambda)(\sec\zeta_{1y} + \sec\zeta_{2y})} \left[A\cos\zeta_{1y} - G(y) \right] + G(y)} \tag{8}$$

where

$$G(u) = \frac{1}{2} P(\psi u) \frac{\sec\zeta_{1u}}{\sec\zeta_{1u} + \sec\zeta_{2u}} .$$

This relation makes it possible to solve graphically or by trial and error for the two unknowns $\tau(\lambda)$ and $A(\lambda)$ for any value of λ at which radiance was measured. The wavelength dependence of A is expected to be slight.

The effect of ozone absorption in the atmosphere has not been formally accounted for. The example of Dave and Sekera (1959) and Coulson (1959) was followed in approximating ozone absorption by taking its effect simply to be that of a "filter" interposed in the path of the solar radiation incident on top of the atmosphere.

Under this assumption, the quantity F_λ in Eq. (7) is multiplied by an equivalent "filter response" function $G(\lambda)$, but the ratio Eq. (8) is not affected.

During the UV measurements presented in this paper, the cloud cover was negligible and therefore no correction for cloud reflectivity or absorption was attempted or needed.

It was not possible to incorporate corresponding IR or visible measurements in this paper since the experimental data for these wavelengths is still incomplete. Further measurements and data evaluation are in progress, and results in the $1.4 - 2.7\mu$ region are expected to reported later.

4. COMPUTATIONS

The values of the scattering angle ψ were computed every two seconds of flight time using an IBM 7090 computer. The origin of time was 80 sec after launch (burnout). The scattering volume was assumed to be located at the ground point G. The neglect of the earth's curvature introduced a maximum difference of $0.6°$ in the value of the scattering angle when the scattering volume was taken at the radiometer instead of at the ground point G. This correction is, of course, independent of the negligible sun parallax over the scattering path, which has been discussed. The sun's position was found by storing the pertinent portions of the Greenwich hour angle and declination tables from the Air Almanac in the computer memory, and letting the computer interpolate linearly between entries whenever it was required. The geographical coordinates of the "ground point" G from which both radiometer and sun positions are reckoned were computed from the known attitudes of the aircraft, as were the zenith angles and azimuths of the radiometer. The required portion of an H. O. 249 table was also stored in memory. Entering this with the latitude of the ground point and the declination and local hour angle of the sun just obtained, the computer determined the required zenith angles and azimuths of the sun, by interpolation. These values were then entered into Eq. (3) above and the scattering angle ψ computed.

A total of 95 values of the ratio R_{xy} in Eq. (8) were computed from experimental values of N_λ for each of the three wavelengths, 0.24μ, 0.26μ and 0.28μ.

The reflectance was allowed to vary from 0.4 to 0.05 in 35 steps of 0.01 and τ was computed. This resulted in $\frac{95!}{2!\,93!} = 4465$ tabulated pairs of A and τ values for each wavelength. Some of these were then plotted on the three scatter plots of Figures 9, 10 and 11, one for each wavelength. Because of the large number of points, only the points of maximum excursion were selected, giving the "perimeter" of the scatter plot. In future calculations this procedure is expected to be refined by having the computer calculate the weighted "centroid" of the scatter plot, thus taking account of the density of points. Also, the range of A will be extended from 0.4 to 1.0.

Taken from Figures 9, 10 and 11 the "most probable" apparent spectral reflectances A and normal optical thicknesses τ for each wavelength are listed in Table 1.

For comparison, Table 2 shows earth albedo values (clear sky) from several references, coded by capital letters.

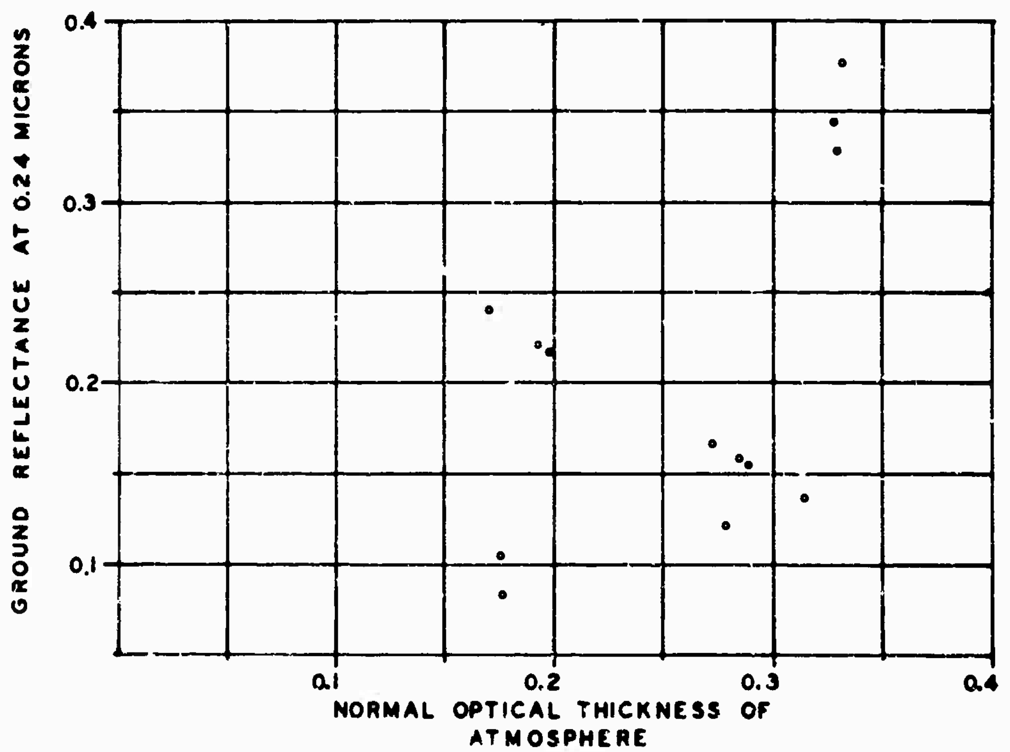

Figure 9. τ versus A at 0.24 Microns

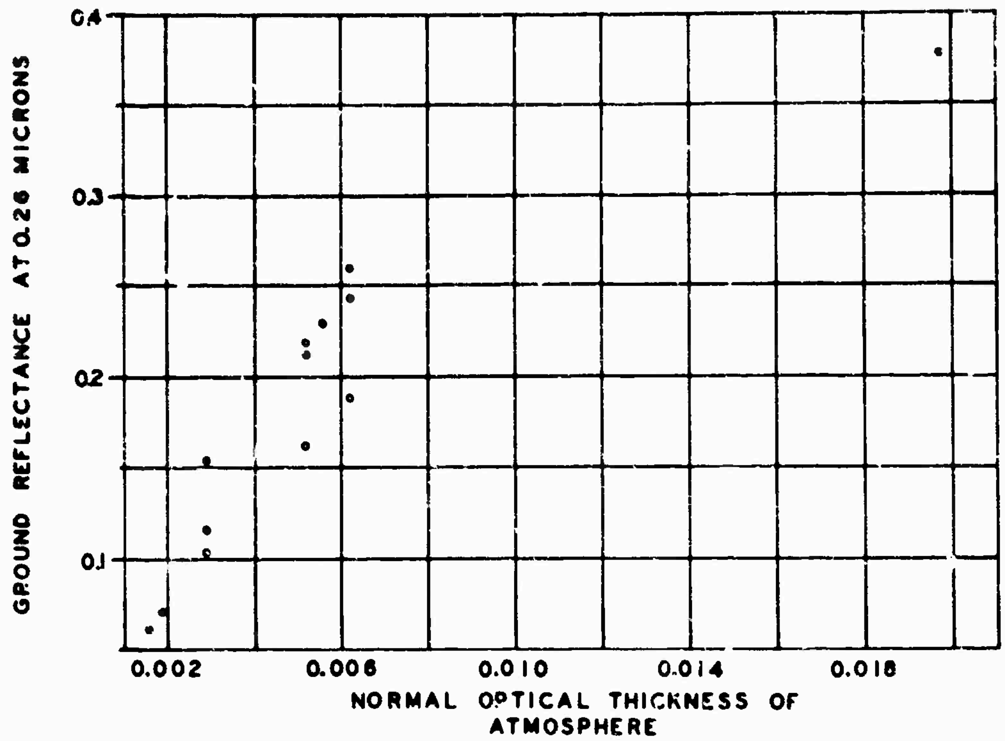

Figure 10. τ versus A at 0.26 Microns

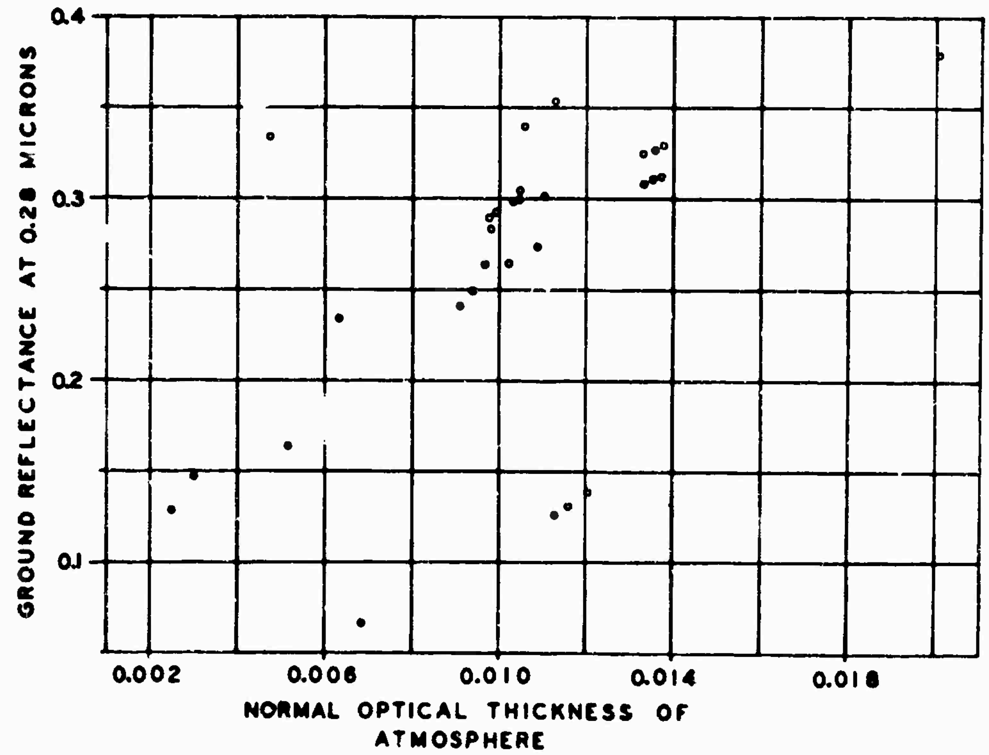

Figure 11. τ versus A at 0.28 Microns

Table 1. Calculated Apparent Ground Reflectance and Normal Optical Thickness

λ(microns)	A (%)	τ
0.24	14 - 24	0.170 - 0.315
0.26	15 - 26	0.005 - 0.006
0.28	24 - 33	0.009 - 0.104

Table 2. Albedo and Reflectance of Various Ground Types, Percent

Forest	3-10	A	
Bare Ground	3-30	A	
Fields, grass, etc.	3-37	A	
Whole earth, total spectrum	35	A	
Whole earth	39	B	
Green forest	3-10	C	
Bare ground	7-20	C	
Wet ground	8- 2	C	
Dry sand	18	C	
Wet sand	9	C	
Mojave Desert	24-28	C	
Death Valley Desert	25	C	
Whole earth (visible spectrum)	39	C	
Whole earth (UV, visible, IR)	35	C	
Whole earth	41.5	C	
Whole earth	29	D	
Forests	5	D	
Deserts	25	D	
Forests, Fields (0.3-3.0μ)	4.5-14	E*	reflectance
Desert, sand, bare rock (0.4-0.8μ)	11-34	E*	
Different types of forests (0.4-0.8μ)	3-57	E*	
Limestone, Clay (visual albedo)	63	F*	
Granite (visual albedo)	12	F*	
Dry sand (visual albedo)	31	F*	
Wet sand (visual albedo)	18	F*	
Coniferous Forest	3-10	F*	
Meadows, grass	3-25	F*	

References - Table 2

A American Institute of Physics Handbook, 1957 edition, p. 2-132.
B Smithsonian Physical Tables, Ninth Revised edition, p. 737.
C Smithsonian Meteorological Tables, Sixth Revised edition, pp. 442-3.
D Kuiper, G. P. (1949) The Atmospheres of the Earth and Planets, U. of Chicago Press, Chicago, pp. 75, 306.
E Möller, F. in Handbuch der Physik 48, Geophysics II, pp. 214-5.
F Handbook of Geophysics, Revised edition (1960), pp. 2-17, 14-1 to 14-7.

* These references contain detailed data on albedo and spectral reflectance in the visible and near infrared region. Entries in Table II are therefore only representative.

5. CONCLUSIONS AND PLANS FOR FUTURE WORK

The results of this investigation show that valid ground reflectance measurements in the 2000-3000 A wavelength range may be possible from high-flying aircraft. Comparison with other published reflectance data is difficult due to lack of coverage of this range, but extrapolation from data (Table 2, reference F) down to 4000 A indicate that our reflectances are about 2 to 3 times larger, assuming sand or desert surfaces. For limestone, clay, etc., surfaces, our reflectance agrees with those in reference F within 10 percent. Integrated reflectance (albedo) data will be compared with ours when our measurements and data evaluation over the visible and near infrared range are completed.

There is considerable doubt from other published work as to whether sufficient UV radiation can actually penetrate the atmosphere twice to yield a valid measure of ground reflectance. For this reason it is planned to extend the data evaluation of the present runs to the time periods during which the radiometer faced away from the earth due to strong rolling and turning of the X-15 vehicle. This should reveal whether there is a measurable contribution to UV reflectance by the ground.

Acknowledgments

The authors wish to acknowledge the assistance rendered by the following individuals: R. Barron and his associates of NASA Laboratories, Edwards AFB, California, and J. Manosh, F. Reslow and A. Eldridge of the Utah State University, Concord Radiance Laboratory.

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1. ORIGINATING ACTIVITY *(Corporate author)* Hq AFCRL, OAR (CRO) United States Air Force Bedford, Massachusetts	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

Spectral Reflectance and Albedo Measurements of the Earth from High Altitudes

4. DESCRIPTIVE NOTES *(Type of report and inclusive date.)*

Scientific Report. Interim.

5. AUTHOR(S) *(Last name, first name, initial)*

BAND, Hans E., and BLOCK, Louis C.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
September 1965	32	5

8a. CONTRACT OR GRANT NO. ARPA Order 363	9a. ORIGINATOR'S REPORT NUMBER(S) AFCRL-65-674
b. PROJECT AND TASK NO. 8662 Task 86621	
c. DOD ELEMENT 62503015	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* AFCRL-65-674
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Spectral radiance measurements over the wavelength range of 0.24 to 0.28 microns were carried out using Ebert-type scanning spectrometers mounted on the aft section of an X-15 aircraft operating up to 270,000 ft altitude. With the assumption of Rayleigh scattering in the atmosphere and allowing for ozone absorption, the reflectance and albedo are estimated and compared with the measured values. The elevations and azimuths of the sun and of the spectrometer during the flight were tabulated and used to compute the scattering and diffuse reflection angles. Apparent reflection of radiation from the ground is estimated, using a Lambert radiator model. Since the spectrometer at times pointed away from the earth, it should be possible to estimate the separate contribution of the ground to the reflectance and total albedo.

DD FORM 1 JAN 64 1473

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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
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